REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 11-02-2003	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE **Investigating the Crack Growth Behavior in a Particulate Composite Material under Multi-Axial Loading Conditions**		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) C.T. Liu		**5d. PROJECT NUMBER** 2302 **5e. TASK NUMBER** 0378 **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRSM 10 E. Saturn Blvd. Edwards AFB, CA 93524-7680		**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-PR-ED-TP-2003-029
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S NUMBER(S)** AFRL-PR-ED-TP-2003-029

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030225 073

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leilani Richardson
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A		**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

FILE

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 03 Feb 2003

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2003-029**
C.T. Liu; M. Tam (Aerospace Co.), "Investigating the Crack Growth Behavior in a Particulate Composite Material under Multi-Axial Loading Conditions"

International Conf. on Mechanical Behavior of Materials **(Statement A)**
(Geneva, Switzerland, 25-29 May 2003) (Deadline: 28 Feb 2003)

Investigating the Crack Growth Behavior in a Particulate Composite Material under Multi-Axial Loading Conditions

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Abstract

In this study, the effects of the applied strain levels on the crack growth behavior in a particulate composite material under a high confining pressure were investigated. The material under investigation contains hard particles embedded in a rubbery matrix. Three strain levels, 12%, 15%, and 18%, and one confining pressures, 8697 KPa, were considered. The experimental data were analyzed and the results were discussed.

Introduction

An important engineering problem in structural design is evaluating structural integrity and reliability. It is well known that structural strength may be degraded during its design life due to mechanical or chemical aging, or a combination of these two aging mechanisms. Depending on the structural design, material type, service loading, and environmental condition, the cause and degree of strength degradation due to the different aging mechanisms differs. One of the common causes of strength degradation is the result of crack development in the structure. When cracks occur, the effects of crack sizes and the rate of growth on the fracture resistance of the material need to be investigated.

In recent years, a considerable amount of work has been done studying crack growth behavior in particulate composite materials under different loading conditions at ambient pressure [1-4]. Experimental findings indicate that power law relationships exist between the crack growth rate, da/dt, and the Mode I stress intensity factor, K_I. These experimental findings support the theory developed by Knauss [5] and Schapery [6] in their studies of crack growth behavior in linear viscoelastic materials. It is known that classical fracture mechanics principles, especially linear elastic fracture mechanics, are well established for single-phase materials. Experimental data indicate that linear fracture mechanics theories are applied to the particulate composite materials with varying degree of success. However, there has been relatively little effort in understanding the crack growth behavior in such materials under confining pressure condition.

In this study, pre-cracked specimens were used to study the crack growth behavior in a particulate composite material, containing hard particles embedded in a rubbery matrix, under constant strain conditions at 8697 KPa confining pressure. Three different applied strain levels, 12%, 15%, and 18%, were considered. The effects of strain levels on the crack growth behavior in the material were investigated and the results are discussed.

2 The Experiments

In this study, specimens with a pre-cracked surface crack were used to determine the crack growth behavior in the particulate composite material subjected to different applied strain levels under an 8697 KPa confining pressures. The geometry of the pre-crack specimen is shown in Fig.1. Prior to conducting the tests, the specimen was loaded in the testing machine inside a pressure chamber. When the pressure inside the pressure chamber reached 8697 KPa, the specimen was straining at a constant strain rate of 8 cm/cm/min. until a per-determined strain level was reached. During the test, a high-speed camera was used to monitor the crack growth on the surface of the specimen. In addition, the load and time were also recorded. These raw data were used to determine the stress, strain, crack length, and crack growth rate.

In order to investigate the effect of the applied strain level on the crack growth behavior in the particulate composite material, the crack growth rates dc/dt, measured on the surface of the specimen, as a function of time were calculated. In calculating dc/dt, the secant method was used. In the secant method, the crack growth rate is computed by calculating the slope of a straight line connecting two adjacent a versus t data points. The calculated average crack growth rate is assigned at a point midway between each pair of data points.

3 Results and Discussion

Experimental results indicate that crack tip blunting takes place both before and after crack growth. The material at the tip of the crack suffers very large elongation and is nearly straight. The highly strained or damage zones extends ahead of the crack tip, appearing as an equilateral triangle with the crack tip as its base. This damage zone is known as the failure process zone, which is a key parameter in viscoelastic fracture mechanics. When the local strain reaches a critical value, small voids are generated in the failure process zone. Due to the random nature of the microstructure, the first void is not restricted to the surface where the maximum normal strain occurs. Since the tendency of the filler particle to separate from the binder under a triaxial loading condition is high, it is expected that voids, or a damage zone, will also be generated in the specimen's interior. Consequently, there are a large number of strands, essentially made of binder material, which separate the voids that form inside the failure process zone. Under this condition, the transverse constant is minimized. As the applied strain increases with time, material fracture occurs at the blunted end of the crack tip. This will always be the location of the maximum local strain. The failure of the material between the void and the crack tip causes the crack to grow into the failure process zone. This kind of crack growth mechanism continues until the main crack tip reaches the front of the failure process zone. When this occurs, the crack tip resharpens temporarily.

The damage and crack growth mechanisms discussed in the above paragraphs are the basic mechanisms observed in this material under both ambient and 8697 KPa pressures. The effect of pressure is to suppress the damage and evolution processes and delay .the onset of crack growth.

It is interesting to point out that for specimen without pre-crack, microcracks start to developed approximately at 30% applied strain and the number of the microcracks increase significantly at 40% applied strain. And, finally, the specimen fracture at 50% applied strain as a result of coalescence of microcracks and propagation of a dominant macrocrack. However, for pre-cracked specimen, the specimen starts to propagate when the applied stress is in the linear region of the stress-strain curve, and there is no significant number of microcracks developed away from the crack tip. Experimental data indicate that in the immediately neighborhood of the crack tip, voids develop in the damage zone.

Typical plots of stress-strain curves under 8697 KPa confined pressure and 18% applied strain are shown in Figs 2. From Fig. 2, it is seen that, under the constant strain condition, the stress decreases as the time is increases, which is a typical stress relaxation phenomenon observed for viscoelastic materials.

Typical plots of crack length, c, versus time, t, for applied strain level equal to 18%, are shown in Fig. 3. Under the constant strain condition, the crack continues to grow a short distance and, then, stop growing after the machine is stopped at the predetermined strain level. This kind of crack growth behavior is believed to be related to the local stress at the crack tip and the viscoelastic nature of the material. When the specimen is under the constant strain condition, the stress will relax. However, the local stress at the crack tip may still be high enough to propagate the crack until the local stress at the crack tip is reduced to a threshold value below which no crack growth can occur. In addition, due to the material's viscoelastic nature, the local time-dependent material response lags behind and is not in phase with the applied deformation. The existence of a time scale or phase change between the applied load and the local response is a possible contributing factor responsible for the continued growth of the crack for a short distance after the machine is stopped.

The determination of the crack growth rate requires an analysis of discrete data relating the instantaneous time, t, to the corresponding crack length, c. Due to the nonhomogeneous nature of the particulate composite materials, the measured data shows a considerable scatter. Therefore, it is anticipated that a smooth and steadily increasing relationship between the crack growth rate and time is difficult to obtain, and the different methods of dc/dt calculation may result in different solutions.

From the results of the crack growth rate calculation, the secant method introduces a pronounced fluctuation of dc/dt, as shown in Fig. 4. In other words, the crack growth process consists of a slow-fast-slow phenomenon. As mentioned earlier, the damage process is a time-dependent process, and it required some time to develop a failure process zone at the crack tip. Thus, the crack growth process consists of blunt-growth-blunt and slow-fast-slow phenomena, which is highly nonlinear. The fluctuation of dc/dt is consistent with experimental observation. Based on experimental evidence, in general, the crack does not grow in a continuous and smooth manner. During the crack growth process, crack growth rate both accelerates and decelerates. Therefore, the secant method appears to provide the best estimate of both the actual crack growth process and the actual crack growth rate.

Referring back to Fig. 4, the crack growth rate continues increase after the machine is stopped at the applied strain level and, then, it starts to decrease to zero velocity.

Conclusions

In this study, the crack growth behavior in a particulate composite material under constant strain conditions was investigated. Experimental findings reveal that the crack continues to grow a short distance and, then, stops after the machine is stopped at the applied strain level. They also reveal that, in general, the crack growth rate decreases as the applied strain level is decreased.

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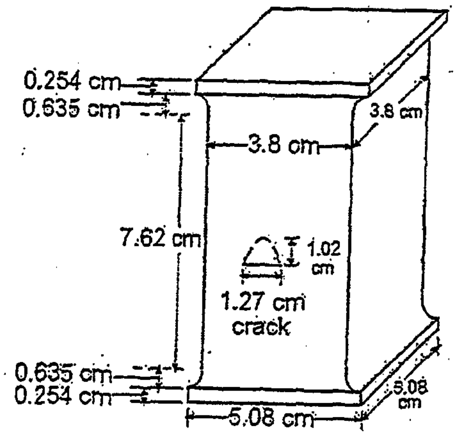

Fig. 1 Specimen Geometry.

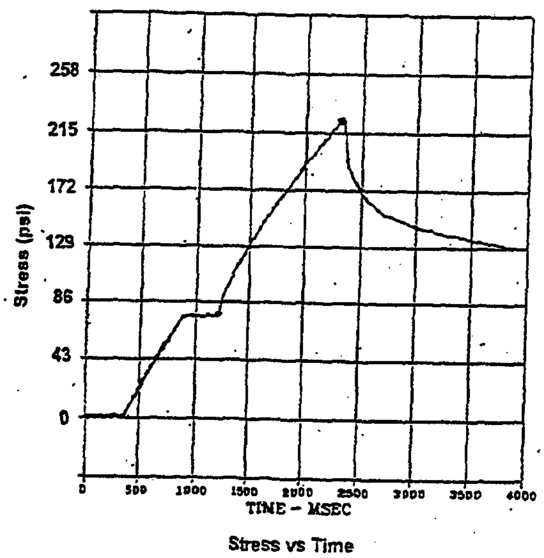

Fig. 2 Engineering Stress versus Strain

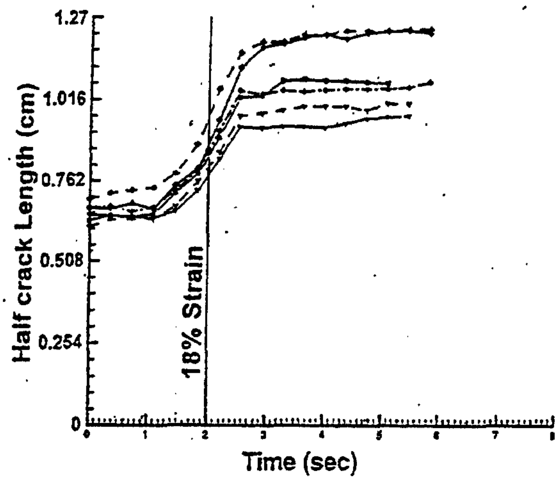

Fig. 3 Half Crack Length versus Time (Applied Strain = 18%)

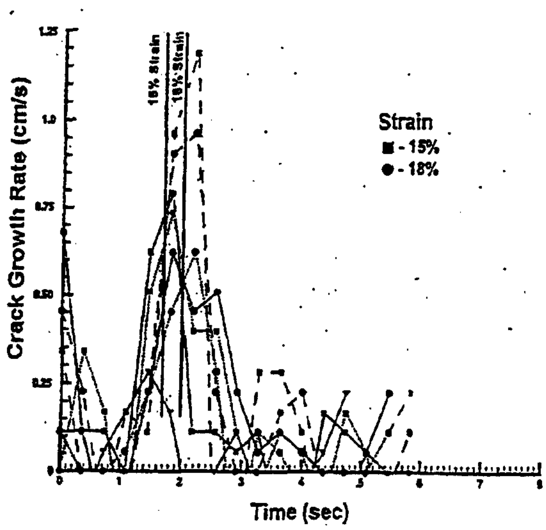

Fig. 4 Crack Growth Rate versus Time.